Sheared-Flow Stabilized Z-pinch Studies: The ZaP and ZaP-High Density Experiments

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for the ZaP Project

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EAT
more lungfish do it [today]
Sheared velocity flow can stabilize a Z-pinch

Sheared-Flow Background

ZaP and ZaP-HD Experiments
- ZaP Results
- ZaP-HD Configuration

Summary and Future Work
The ZaP and ZaP high density (ZaP-HD) experiments use sheared-flow stabilization to produce long-lived Z-pinches.
- Quiescent plasmas last thousands of Alfvén times and several flow-through times.

Low MHD mode activity is correlated with sheared plasma flow.

Quiescent plasmas can be maintained as long as the plasma source and current persists.

ZaP-HD will study sheared-flow stabilization scaling to higher densities.
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Sufficient Sheared-flow Stabilizes a Z-Pinch

- Linear stability applied to marginally-stable Kadomtsev equilibrium
  \[-\frac{d \ln p}{d \ln r} = \frac{\gamma}{2 + \gamma \beta}\]

- In the no-wall limit, \(r_w > 4a\), stability seen for
  \[\frac{dV_z}{dr} \equiv V_z' \geq 0.1kV_A\]

- Destructive interference and phase mixing from sheared flow
Gas is injected and capacitor is discharged.

Plasma accelerates down the coaxial accelerator until it assembles into a Z-pinch plasma along the axis.

Inertia and gun currents maintain the flowing plasma state until the accelerator plasma empties or current diminishes.
ZaP and ZaP-HD Experiments

ZaP — Original coaxial experiment using sheared-flow stabilization

ZaP-HD — New triaxial experiment investigating scaling toward HEDP
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor bank energy</td>
<td>$E_{\text{cap}}$</td>
<td>144 kJ (max)</td>
</tr>
<tr>
<td>Charge voltage</td>
<td>$V_c$</td>
<td>10 kV (max)</td>
</tr>
<tr>
<td>Plasma current</td>
<td>$I_p$</td>
<td>480 kA (max)</td>
</tr>
<tr>
<td>Pinch radius</td>
<td>$a$</td>
<td>0.5–1 cm</td>
</tr>
<tr>
<td>Pinch length</td>
<td>$\ell_p$</td>
<td>50–126 cm</td>
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<tr>
<td>Electron density</td>
<td>$n_e$</td>
<td>$10^{16}$–$10^{17}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma temperature</td>
<td>$T_e + T_i$</td>
<td>150 – 250 eV</td>
</tr>
<tr>
<td>Plasma lifetime</td>
<td>$\tau_p$</td>
<td>20 – 100 $\mu$s</td>
</tr>
</tbody>
</table>

Working gas is hydrogen
Diagnostics Measure Plasma Flow & Stability

ZaP diagnostics measure equilibrium plasma parameters, plasma flow, and magnetic mode activity (stability).

- Surface-mounted magnetic field probes
  - Analyze magnetic fields, magnetic fluctuations, and plasma stability
- Fast framing camera with optical filters
  - Qualitative measure of plasma structure
- Four-chord, visible HeNe interferometer
  - Measure plasma density profile
- 0.5 m imaging spectrometer with 20 input chords and an intensified CCD detector
  - Doppler shift for plasma flow profile, Doppler broadening for ion temperature, Zeeman splitting for magnetic fields, Stark broadening for density
- Digital holographic interferometer
  - Measure two-dimensional plasma structure
ZaP Has Used Several Electrode Configurations

- Gas injection
  - z = -75
- ICCD
  - z = -25
  - z = 0
  - z = 25
- Solid end wall
- 50 cm extension
- Open end wall

(a) 10 cm hollow inner electrode

(b) 10 cm inner electrode with nose cone

(c) 16 cm inner electrode

Rod electrode
“Quiescent period” defined for normalized azimuthal mode data $\leq 0.2$ (displacement of a plasma radius).

$\approx 37 \, \mu s$ quiescent period
(Instability growth time $\approx 20 \, \text{ns}$; flow through time $\approx 10 \, \mu \text{s}$)
Flow Profile is Correlated to Plasma Stability

- $\tau < 0$, plasma assembly, axial plasma velocity is high and uniform, $v'_z \simeq 0 - 4 \times 10^6 \text{ s}^{-1}$
- $0 \leq \tau \leq 1$, quiescent period, the velocity profile is high at the plasma edge and lower at the axis, $v'_z \simeq 7 - 12 \times 10^6 \text{ s}^{-1}$
- At a point during the quiescent period, the edge velocity slows so the velocity is higher at the axis than the edge.
- $\tau > 1$, end of quiescent period, the plasma velocity profile is low & uniform, $v'_z \simeq 0 - 6 \times 10^6 \text{ s}^{-1}$

Theoretical growth time is $\simeq 20 \text{ ns}$

Shear threshold is $\simeq 5 \times 10^6 \text{ s}^{-1}$
ZaP Shows Evidence for Long-length Pinches

Magnetic data up to 86 cm from inner electrode show quiescent pinch of nearly constant field

Interferometer data 57 cm from inner electrode show density peaked on axis

End of inner electrode is at $z = -17$ cm
Viscosity Shear Damping Time Allows Long Pinches

Viscous damping time:

\[ \tau_\mu \approx \frac{\rho L_v^2}{\mu} \]

Unmagnetized \( \mu \) (Spitzer Eq. (5-54) in SI–eV units):

\[ \mu = 1.52 \times 10^{-25} \frac{T^{5/2} A_i^{1/2}}{Z^4 \ln \Lambda} \]

Magnetized \( \mu_\perp \) (Eq. (5-55)):

\[ \mu_\perp = 2.89 \times 10^{-4} \frac{A_i^{3/2} Z^2 n_i^2 \ln \Lambda}{T_i^{1/2} B^2} \]

\[ \Rightarrow \text{Viscous damping time } \approx 1 \text{ m flow-through time} \]
Experimental Modifications Confirm the No-wall Limit

Close-fitting conducting walls can stabilize, providing an alternative explanation to the observed stability. To test the no-wall limit, a section of the outer electrode is inserted which contains large perforations.

Experimental results show no effect of the perforated section.
Correlation of Stability with Plasma in Acceleration Region

With large gas load (using larger inner electrode) the quiescent region lasts as long as the current pulse.
Extending the Plenum Increases Gas Supply

- ZaP insulator configuration increased in length
- The PTFE (Teflon) extension is shielded from the plasma
  - PTFE is vulnerable to plasma interaction and degrades with time
- An additional alumina insulator is used on the downstream face of the series
- Insulated volume is increased by approximately 300%
Larger Plenum Allows Accelerator Operation Throughout Pulse

- Density at end of acceleration region shows longer persistence with larger plenum (green trace)
Summary of ZaP Results

ZaP demonstrates evidence of flow-shear stabilization of a Z-pinch:

- MHD stability correlated with sheared velocity

- Stability lasts as long as there is flow shear, plasma in the acceleration region, and the power supply current persists

- Stability period increased with increasing pinch length

- Removal of a large section of the outer wall did not affect stability

- Larger plenum results in longer persistence of plasma in acceleration region

Nelson et al. (Univ. Wash.)

ZaP and ZaP-HD

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Adiabatic pinch scaling for a Bennett equilibrium:

\[
\frac{d}{dt} \left( \frac{p}{n^\gamma} \right) = \frac{d}{dt} \left( \frac{(1 + Z) kT}{n^{\gamma-1}} \right) = 0; \quad (1 + Z) NkT = \frac{\mu_0 I^2}{8\pi}
\]

ZaP–HD is designed as an intermediate step toward HEDP (\(~ 1\) Mbar)
ZaP and ZaP-HD Parameters

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<td>$I_p$</td>
<td>150–480 kA</td>
<td>250 kA (Accel)</td>
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<td></td>
<td></td>
<td></td>
<td>500 kA (Comp)</td>
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<td>0.2–0.3 cm</td>
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<td>Pinch length</td>
<td>$\ell_p$</td>
<td>50–129 cm</td>
<td>53 cm</td>
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<tr>
<td>Electron density</td>
<td>$n_e$</td>
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Working gas is hydrogen

Nelson et al. (Univ. Wash.)
Gas is injected and bank 1 is discharged.

Plasma accelerates down the coaxial accelerator until it assembles into a Z-pinch plasma along the axis.

Bank 2 is discharged to compress plasma to higher energy densities.

Inertia and gun currents maintain the flowing plasma state until the accelerator plasma empties or current diminishes.
Initial ZaP-HD operations focus on optimizing the accelerator.

The axial surface probe array shows the plasma rundown in the accelerator.

Fast Imacon camera images (2 µs apart) show symmetrization of the plasma breakdown.
Summary & Future Work

Summary:

- ZaP shows long-length (1 m) Z-pinches, stable for thousands of Alfvén times and several flow-through times

- Stability correlated with presence of sheared-flow, a source of accelerated plasma, and power supply current

- Stability shown to not be affected by conducting wall

Future Work:

- ZaP-HD will study scaling of flow-shear stabilized Z-pinches to higher densities, approaching HEDP

- The acceleration and compression power supplies can be independently controlled

- ZaP-HD beginning operations
Tom Intrator, Chung Chan, and Noah Hershkowitz
ca. 1982